Muon pair production by photons in atmosphere: Is any room left for high-energy muon astronomy?

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Abstract

Production of muon pairs by high-energy photons in electromagnetic and hadronic showers in atmosphere has been calculated. The effect of muon pair production in hadronic Extensive Air Showers (EAS) is unlikely to be seen by next generation detectors. Applications of muon pair production process in electromagnetic showers to the very high energy gamma-ray astronomy is discussed. It is shown that, although this process dominates over conventional pion and kaon decay above a few TeV in photon-initiated showers and provides a distinctive signature of photon-induced event (muon pair), it is practically impossible to discriminate such events statistically from the background of muon pairs produced in the hadronic EAS. The rate of events is very low and requires detectors of a huge size.

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1. Introduction

Muon pair production in electromagnetic showers in atmosphere has been considered in the middle of 1980s by Kudryavtsev and Ryazhskaya [1] and Stanev et al. [2] in connection with observed muon excess from Cyg X-3 [5, 6]. Stanev [3] and Berezinsky et al. [4] discussed high-energy gamma-ray astronomy using underground detectors. Recently muon pair production in hadronic Extensive Air Showers (EAS) has been calculated [7].

Underground muon data from the MACRO [8] and LVD [9] experiments did not reveal any excess from any region of the sky or any source detected at TeV energies by Cherenkov telescopes. In fact, the sensitivity of the existing underground detectors is not enough for such a detection assuming known processes of muon production with known cross-sections used in the calculations mentioned above. However, only experimental search for possible excess with underground detectors can really provide information about processes of acceleration at sources, muon production mechanisms and possibly give some indications about new physics.

High-energy gamma-ray astronomy with muons was discussed also in a few recent papers [10, 11]. Halzen et al. [10] considered photoproduction of muons below 1 TeV and found that future 1 km^3 underwater/under-ice neutrino telescopes (see, for example, [12, 13]) can be able to detect muons associated with high-energy photons from point sources. Bhattacharyya [11] calculated gamma-induced muon flux from the Crab Nebula and obtained a value within a reach of future neutrino telescopes.

Previous calculations, however, have been performed using one-dimensional model which restricted the analysis of the detector sensitivity. No muon propagation in rock or water was included in the calculations so far. At present powerful three-dimensional Monte Carlo codes for development of the showers in the atmosphere (for example, CORSIKA [14]) make possible full simulation of electromagnetic, hadronic and muonic components of EAS produced by any primary particle. Muons can be propagated through the rock or water down to observation level using three-dimensional transport codes. This allows calculation of detector sensitivity to photon-induced muons taking into account effects of muon scattering in atmosphere and rock.

In this paper we present new calculations of muon production in photon-induced showers in atmosphere using three-dimensional simulations. We also used three-dimensional transport of muons through rock and water to estimate sensitivity of existing and future detectors. We are interested primarily in high-energy muons ($E_\mu \geq 100$ GeV) capable of reaching deep underground/underwater experimental facilities. We concentrate mainly on direct muon pair production by photons because this process can give a distinctive signature of gamma-induced event (muon pair with small separation). We also present calculations of muon pair production in hadronic showers. The paper is organised in the following way. In Section 2 we describe method of calculation. In Section 3 we show the results for muon pair production in hadronic showers and compare them with previous calculations. Section 4 contains the results for muon production in electromagnetic showers and comparison with earlier calculations. We discuss applications of our results for gamma-ray astronomy in Section 5. The conclusions are given in Section 6.

2. Method of calculations

Extensive Air Showers (electromagnetic and hadronic) at vertical were simulated using CORSIKA Monte Carlo code [14]. Hadronic showers were produced by vertically incident protons with power-law spectrum with index $\gamma = 2.7$. For evaluation of muon intensities and yields we used differential primary spectrum of all nucleons in the form: $1.8 \times E^{-2.7}$ nucleons/(cm^2 s sr GeV)$^{-1}$ [15]. For a given energy per nucleon heavy primaries will produce more muons and photons than proton primaries. Since the number of muons and photons in a shower is proportional to the atomic weight of primary nucleus (in accordance with our simulations), our approach to use all-nucleon spectrum is justified regardless of the primary cosmic-ray composition.

Primary photons were assumed to have energy spectrum with power index $\gamma = 2.1$ and $\gamma = 2.5$. Two different assumptions were made about high-energy cut-off. In the first optimistic case no cut-off was included in the simulations. This may correspond to the nearby gamma-sources with accelerated protons producing high-energy photons. In the second, more realistic, case high-energy cut-off was assumed to be equal to 100 TeV.

Muon pair production by photons is included in the complete version of the CORSIKA code. In an ideal case most important processes of muon production (conventional pion and kaon production and decay, and direct muon pair production) can be simulated in CORSIKA. In practice, we need many thousands or even many ten thousands muons at surface to estimate detector sensitivity underground. Such a statistics can be easily obtained for conventional muon production in hadronic showers. The probability of muon production in electromagnetic showers is at least one order of magnitude less. This requires much higher statistics for simulated electromagnetic showers. To overcome this difficulty we used CORSIKA to simulate conventional muons (from pion and kaon decay) and to obtain average atmospheric depth profiles of photons with various energy thresholds in electromagnetic and hadronic showers. Average depth profiles of photon fluxes from CORSIKA output were then used to simulate muon pair production by photons. Thus, we separated muon pair production by photons from the development of the shower. The advantage of this is the dramatic reduction in the CPU time needed to obtain sufficient statistics for underground muons. The CPU consumption is driven by the statistics for photons in atmospheric showers. The disadvantage is the impossibility to consider two muon pairs or muon pair and muons from pion decay in the same shower. Note, however, that the probability of muon production in an electromagnetic shower is quite small and is certainly much less than 1 for all muon and photon energies important for further considerations (only values of x within the region $10^{-3} < x = E_\mu/E_\gamma < 1$, where E_μ is the muon energy and E_γ is the initial photon energy, contribute to muon production). This means that it is unlikely to have two direct muon pairs or direct muon pair and conventional muons in the same shower. Further muon propagation through the rock/water also suppresses muon multiplicity. As we will show later on, at all energies the integral probability of direct muon pair production (muon yield) is less than 10^{-3} in an electromagnetic shower and, then the probability to have two muon pairs in the same shower is on average 10^{-3} times less. At low muon energies the conventional muon yield may be quite high but again the small probability of direct muon pair production does not add much to the resulting muon flux.

We checked our simulations of photons in EAS with CORSIKA against experimental data at high altitudes. Simulated flux of electromagnetic component (photons, electrons

and positrons) with energy more than 5 TeV as a function of atmospheric depth is plotted in Figure 1 (solid curve) together with our calculation using parameterisation given by Gaisser [15] (dashed line). Figure 1 shows that measured atmospheric depth profile of photon flux agrees better with our simulations using CORSIKA. There is still a discrepancy at depths more than 400 g/cm^2. More than 90% of photons in the showers, however, are above this depth where the agreement between simulations and measurements is pretty good.

Muon pair production by photons was simulated using differential cross-section for muon bremsstrahlung [17]. This cross-section can be easily converted to muon pair production cross-section by reversing particles in initial and final states. The muon pair production cross-section as a function of photon energy is shown in Figure 2 for two minimal values of fractional energy transfer: $x_{min} = E_{\mu min}/E_\gamma = 0.01$ (solid curve) and $x_{min} = 0.1$ (dashed curve). The cross-section does not change much with the decrease of the lower limit of integration (x_{min}) below 0.01.

Angles of muons in the final state were sampled according to the method used in GEANT [18]. Further transport of muons in atmosphere was done using a specially developed version of three-dimensional muon propagation code MUSIC (standard version of the code is described in Ref. [19]). We found that muon deflection at production and multiple scattering in the atmosphere contribute significantly to the lateral separation of muons in pairs underground. Muon deflection at production is important for muon separation at shallow depths (low muon energies) since mean deflection angle is proportional to m_μ/E_μ. Note, that since the air density varies strongly with atmospheric depth, the step along muon path to calculate deflection due to multiple scattering should be small. For comparison, we calculated also muon separation underground without accounting for muon deflection at production and/or multiple scattering in atmosphere.

Muon transport through rock or water down to the observation level was done using standard version of muon propagation code MUSIC [19].

3. Muon pair production by photons in hadronic showers

Muon pair production is negligible compared to the conventional muon production at TeV energies. Due to the competition between interaction and decay for pions and kaons, however, power index of conventional muon spectrum is about 3.7 while direct muon energy spectrum is harder with power index $\gamma = 2.7$. This implies that at some energy direct muon pair production may dominate over conventional muons (see [7] for detailed discussion). Our three-dimensional calculations of vertical EAS initiated by primary protons show that the ratio of direct muons to pions decreases from 2.4×10^{-5} at 10 TeV down to 1.6×10^{-5} at 1000 TeV assuming constant slope of pion spectrum. The decrease of the ratio is due to the steepening of the photon spectrum with energy. In the simulations we use constant slope of primary spectrum at all energies. The change of the slope at and above the "knee" will affect absolute values of pion, photon and muon fluxes but is unlikely to change significantly the ratio of direct muons to pions and conventional muons. The calculated ratio of direct muons to pions is smaller than that obtained in Ref. [7], where parameterisation from Ref. [15] for photon flux as a function of energy and depth in atmosphere was used. The formula in Ref. [15] was obtained assuming scaling parameterisation of the inclusive spectra and constant cross-sections. It does not

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fit measured atmospheric profile of photon flux (see Figure 1 for comparison).

We simulated a sample of helium- and iron-induced showers and found that for the same energy per nucleon the numbers of muons and photons in EAS are proportional to the atomic weight of primary nucleus. We concluded that our approach to use primary spectrum of all nucleons is justified regardless of the precise composition of primary cosmic rays. If heavy nuclei dominate at energies above $10^{15} - 10^{16}$ eV, however, mean muon multiplicity per shower will be higher than for proton primaries. Muons from direct photoproduction dominate over conventional muons at vertical at energies higher than 1.5×10^{16} eV (the intersection point at 3×10^{15} eV was obtained in [7]). It is hard to predict, however, the spectra of conventional muons and direct muons near and beyond the region of the "knee" in the primary spectrum. Note, that muons from charm particle decay may dominate in the total muon flux at these energies since most models predict the ratio of charm-produced muons to pions larger than or about 10^{-4}.

The number of directly photoproduced muons with energy higher than 10^3 TeV is about 5 per year per steradian for 1 km^2 detector, while corresponding number of conventional muons is about 30 at vertical. Both numbers suffers from large uncertainties in the primary spectrum, its composition and model of nucleus-nucleus interaction at high energies.

It is unlikely that even future 1 km^2 neutrino telescopes, capable of measuring muon energy, can detect and discriminate directly photoproduced muons from conventional muons and/or prompt muons (from charmed particle decay). Although direct muons have a distinctive feature, such as flat zenith angular distribution (similar to that of prompt muons), the number of events is too small for this feature to be seen. At energies about 100 TeV those events are hidden by much larger number of conventional muons. At higher energies (more than 1000 TeV) the number of events is too small and many years of exposure are needed to collect reasonable statistics. Moreover, it is likely that prompt muons dominate in the total muon flux at these energies. It is not clear also how sensitive neutrino telescopes will be to the down-going muons, how accurately they can measure muon energy etc.

4. Muon pair production by photons in electromagnetic showers

To quantify muon pair production by photons in electromagnetic showers we used the same approach as in Ref. [4]. We characterised muon pair production by its yield, i.e. the ratio of muon flux above given energy to primary photon flux above the same energy, $r_\mu(> E) = F_\mu(> E)/F_\gamma(> E)$.

At first we checked the yields of directly photoproduced muons and conventional muons from the CORSIKA code itself. We found the yield for directly photoproduced muons to be about $(3 - 6) \times 10^{-5}$ for energy $E = 1 - 10$ TeV and primary index $\gamma = 2.1$, which is a few times less than obtained in Ref. [4]. Much higher statistics (and more CPU time) is required for better estimate of the direct muon yield in CORSIKA. Observed discrepancy supports our decision to use home-made programs with cross-section valid at high energies [17] to simulate muon pair production in atmosphere.

Results of the simulations are shown in Table 1 together with earlier calculations from Ref. [4]. 10^6 showers were simulated for each case giving the statistics for conventional

muon yield $r_\mu(> E) \times 10^6$ (for example, 1802 muons were obtained for $E = 0.1$ TeV and $\gamma = 2.1$, which gives the value of yield $r_\mu(> E) = 1.8 \times 10^{-3}$ in Table 1). This makes the results for conventional muons quite uncertain at threshold energies $E >> 1$ TeV. However, at such energies the contribution of this process to the total muon flux is quite small. Much higher statistics was achieved for direct muon production at these energies since the average atmospheric depth profile of photons was used to simulate this process independently of the development of a particular shower. Our simulations are in reasonable agreement with previous results [4]. Note, that the calculations in Ref. [4] have been performed semi-analytically within Approximation A of the cascade theory without full Monte Carlo. The observed difference (less than a factor of 2 for all energies and spectral indices) can be explained by more adequate model of photopion production in CORSIKA and/or by precise treatment of the development of electromagnetic shower in atmosphere.

Differential muon spectra in electromagnetic showers at sea level at vertical for 1 TeV and 10 TeV primary photon energies are shown in Figure 3. The suppression of the spectra at low energies is due to the muon decay in the atmosphere.

Good agreement between present Monte Carlo simulations and previous semi-analytical computations [4] in terms of muon yields from various processes proves that main conclusions of Ref. [4] are still valid. Since the end of 1980s, however, very high energy gamma-ray astronomy made significant progress (see [20, 21, 22] for recent reviews). A number of galactic and extragalactic sources has been detected at TeV energies, the Crab Nebula being the brightest of them. Typical fluxes from the sources or upper limits from ground-based observations by existing atmospheric Cherenkov telescopes are of the order of 10^{-11} photons/(cm^2 s) at 1 TeV. Recent results from ground-based telescopes can be used now to estimate the sensitivity of underground/underwater/under-ice detectors to muons produced in electromagnetic cascades.

We started with the brightest source – the Crab Nebula. The differential energy spectrum from this source can be approximated as $3 \times 10^{-11} \times (E/\text{TeV})^{-2.5}$ photons/(cm^2 s TeV) (see [21] and references therein). Assuming no high-energy cut-off of the spectrum, the flux of directly photoproduced muons from the Crab Nebula is 9.5×10^{-16} cm^{-2} s^{-1} above 1 TeV at surface. Muon flux from the Crab Nebula was also calculated in Ref. [11]. Although the author of Ref. [11] assumed smaller photon flux from the source above 1 TeV (integral spectrum $1.07 \times 10^{-11} \times (E/\text{TeV})^{-1.4}$ photons/(cm^2 s) against $2.0 \times 10^{-11} \times (E/\text{TeV})^{-1.5}$ photons/(cm^2 s) assumed in present simulations) the muon flux from direct pair production quoted in Ref. [11] is several times higher than our result. To calculate the flux from muon pair production Bhattacharyya [11] followed analytical procedure developed by Berezinsky et al. [4]. However, he used photopion production cross-section (0.332 mb, see eq.(8) in Ref. [11]) instead of muon pair production cross-section (asymptotic value ≈ 0.022 mb as in Figure 2 and Ref. [4]).

The flux of conventional muons from the Crab Nebula above 1 TeV at surface is 1.5 times larger (1.5×10^{-15} cm^{-2} s^{-1}) than that of direct muons. Again this value is several times smaller than the flux calculated in Ref. [11].

Similar considerations applied to the "standard" source with integral spectrum $10^{-11} \times (E/\text{TeV})^{-1.1}$ photons/(cm^2 s) reveal the following fluxes above 1 TeV: 1.26×10^{-15} cm^{-2} s^{-1} from direct muon pair production and 3.05×10^{-15} cm^{-2} s^{-1} from pion and kaon decay. This corresponds to 1360 muons with energy at surface above 1 TeV which can be observed by a detector with effective area of 1 km^2 per year. The number of background

atmospheric muons in a cone with half-angle $1°$ is 1.6×10^7. This gives a signal-to-noise ratio $S/\sqrt{N}$=0.34. The ratio decreases with decreasing energy threshold and detector area. The high-energy cut at 100 TeV reduces the number of muons from the source by a factor of 3. Our results are more pessimistic than calculations by Halzen et al. [10] due to the difference in the photon fluxes used in the calculations. We used measured photon fluxes at about 1 TeV (see, for example, Ref. [21] and references therein) while Halzen et al. [10] extrapolated photon spectra measured at about 100 MeV to TeV energies.

5. Sensitivity of underground/underwater detectors to muons from point sources

Better way to estimate the sensitivity of underground/underwater detectors to muons from gamma-ray sources is to calculate the characteristics of muons fluxes at the detector site, namely, energy spectra, lateral and angular distribution of photoproduced muons together with muon background. We consider here three types of underground/underwater detectors: i) existing underground detectors, like MACRO and LVD (see, [8, 9] and references therein for detector description), with good spatial and angular resolution but incapable of measuring energy of through-going muons, their surface area is of the order of 1000 m^2, ii) shallow depth underground detectors, like LEP experiments (for Cosmo-LEP project see [23, 24]), with relatively small area (about 100-200 m^2) but good spatial, angular and energy resolution, and iii) existing and future underwater/under-ice neutrino telescopes, like AMANDA [12] and ANTARES [13] with effective area of 1 km^2.

We assumed that detector of type i) is at the depth of 3 km w.e. of standard rock, detector of type ii) is at the depth of 0.3 km w.e. of standard rock and detector of type iii) is at the depth of 2 km of water/ice. We assumed also that integral gamma-ray spectrum from "standard source" can be approximated as $10^{-11} \times (E/\text{TeV})^{-1.1}$ photons/(cm^2 s) above 100 GeV without high-energy cut-off. The cut-off at 100 TeV reduces the muon flux above 1 TeV by a factor of 3 if power index of differential spectrum is $\gamma = 2.1$. If $\gamma = 2.5$, the reduction does not exceed 30%. We considered only vertical muons and only one depth for each detector specified above. Realistic slant depth distribution is important for any particular experiment but cannot change qualitatively our results.

Detector of type i) at 3 km w.e. will detect 0.85 muons per year per 1000 m^2 of effective area. It is obvious that none of existing or planned underground detectors is able to discriminate such a tiny flux from the background which is of the order of 6000 muons in a cone with half-angle $1°$ (solid angle of about 10^{-3} sr). Number of double muon events from direct muon pair production is 0.054 with additional (50-70)% contribution from pion and kaon decays. Average lateral separation of direct muons in pairs is of the order of 3 meters, which is less than typical separation of muons in muon bundles originated in hadronic EAS. There is no way, however, to use this feature for definite detection of muons from the source.

At the depth of 0.3 km w.e. muons from pion and kaon decays dominate and the contribution of direct muons is negligible. Number of muons from the "standard source" which can be detected by 100 m^2 detector is about 17 per year. The muon background from hadronic showers is about 6.8×10^5 in a cone with half-angle $1°$. Again, the statistics for the signal is too small for positive detection of the source. The number of double muon events from both direct muon production and conventional muon source is about 1 per

year per 100 m^2 which is much smaller than the number of background double muon events initiated in hadronic EAS. The spread of muons in double muon events is large (several ten meters for both signal and background). Detectors of type ii) are able to measure muon energy using magnets. With increasing energy threshold the signal-to-noise ratio increases, in particular, for double muon events, but this does not help to detect the signal because of significant reduction in the number of expected events. In the simulations we neglected the decay of directly produced muons which will have only minor effect on muon intensities above 50 GeV at vertical.

Finally, at the depth of 2 km in water or ice 1 km^2 detector will detect about 2500 muons with energy higher than 100 GeV (typical energy threshold for through-going muons for such a detector) per year. The number of background muons is about 1.4×10^7 muons per year in an 1° half-angle cone. The signal-to-noise ratio is about 0.67 which is not enough for positive detection of the signal from the source. Moreover, part of muons from the source are coming in groups which can be seen as single muons, thus reducing the total number of detected events. Assuming that such a detector can estimate muon energy, the software energy threshold of 1 TeV for through-going muons can be applied but is unlikely to change the situation in favour of the signal. The number of background muons in this case is 1.1×10^6, while about 540 muons from the source can be detected with signal-to-noise ratio of about 0.5. The use of double muon events with small separation between muons as a signature for muon pair production is doubtful because it is not known at present how such a detector can discriminate multiple muon events from single muons.

Muon production in electromagnetic showers has been recently considered by Fassò and Poirier [25] and Poirier et al. [26]. These authors presented detailed simulations of muons in electromagnetic showers using FLUKA Monte Carlo code [27] (without muon pair production) in application to the GRAND [28] and Milagro [29] experiments. They concentrated on the characteristics of muon flux but did not discuss the sensitivity of detectors to muons from astrophysical gamma-ray sources. Conventional muon yields obtained in present work with CORSIKA (QGS model with jets) are in reasonable agreement with the results from FLUKA [25]. For 1 TeV and 10 TeV primary photons muon spectra from CORSIKA are about 20% lower than corresponding results from FLUKA [25]. Extrapolation of our results from ≈100 GeV down to ≈1 GeV (for signal and background muon spectra) shows that the signal-to-noise ratio remains much less than 1. It is not obvious, however, that such an extrapolation is a correct procedure for photon spectra from point sources since they have not been measured directly at 1-500 GeV. There is still a possibility that at GeV energies photon fluxes are higher than expected from such a simple extrapolation. Only future measurements of (or upper limits on) the fluxes of photons or muons at these energies will provide necessary information.

The possibility to use muons as detectors of gamma-ray bursts was discussed by Halzen et al. [10] and Alvarez-Muñiz and Halzen [30], but is beyond the scope of present study.

6. Conclusions

The calculations presented here were based on the measured very high energy gamma-ray fluxes from a number of sources and the limits on the fluxes from some other point sources. Our simulations show that the expected high-energy muon fluxes undergro-

und/underwater/under-ice are too small (also in comparison with muon background) to be detected by existing and planned detectors including large-scale neutrino telescopes. Specific signatures of high-energy muon events initiated by photons (muon pairs with small lateral separation of muons) does not help to detect signal. High-energy muon astronomy can survive if i) extremely powerful steady, pulsed or (most likely) burst sources of very high energy photons exists in the Universe; ii) a new channel of muon production is found or the cross-section(s) of the process(es) which lead(s) to muon production at high energies is (are) much higher than expected; iii) a new neutral, stable, strongly interacting particle substitutes photon in muon production. However, only continuous monitoring of the sky can help to answer these questions.

Acknowledgments

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Table 1: Muon yields (ratio of muon flux to primary photon flux above the same energy $r(E) = F_\mu(> E)/F_\gamma(> E)$) multiplied by 10^6 for various energies E and indices of primary spectrum γ. The row $\gamma \to 2\mu$ shows the yield of direct muon pair production, $\pi, K \to \mu$ shows contribution from conventional muons.

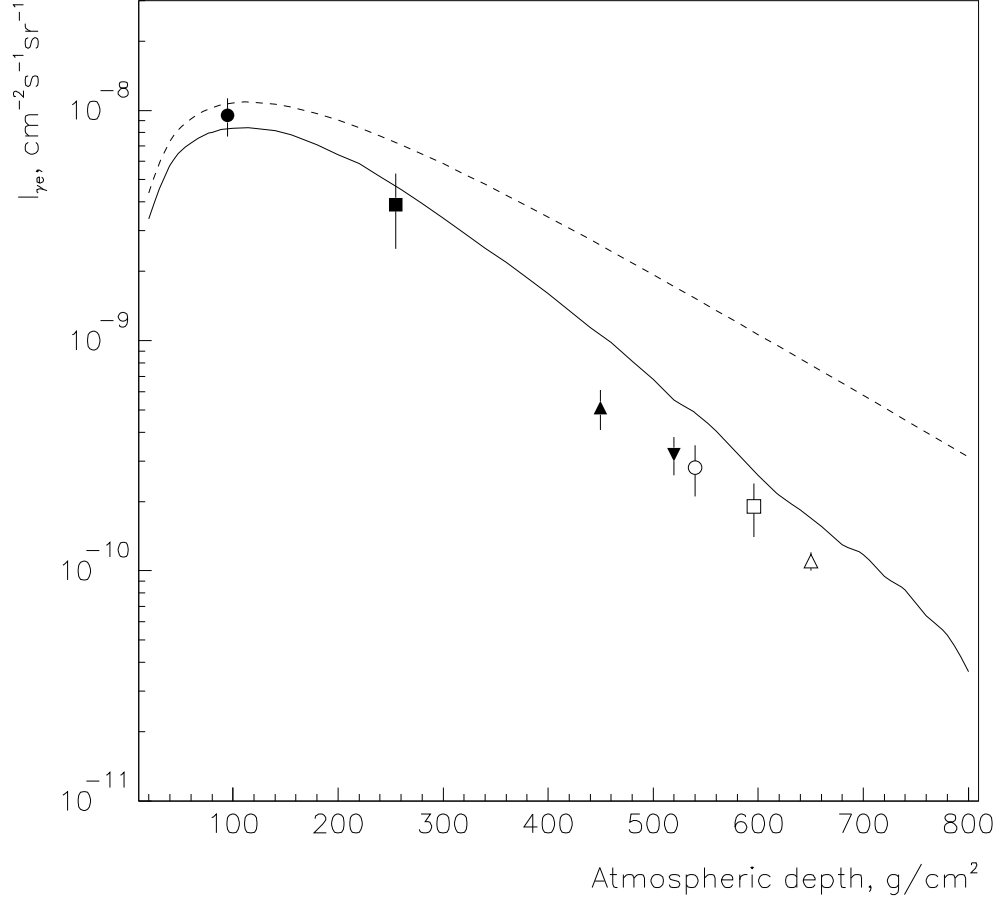|		2.1	2.1	2.1	2.5	2.5	2.5
	γ						
	E, TeV	0.1	1	10	0.1	1	10
This work	$\gamma \to 2\mu$	95	127	126	32	47	56
	$\pi, K \to \mu$	1802	305	35	386	76	9
	sum	1897	432	161	418	123	65
[4]	$\gamma \to 2\mu$		156	181		25.5	30.4
	$\pi, K \to \mu$		358	40		42.0	4.7
	sum		514	221		67.5	35.1

Figure 1: Integral flux of electromagnetic component (photons, electrons, positrons) with energy more than 5 TeV as a function of depth in atmosphere. Solid curve – present simulations with CORSIKA, dashed curve – parameterisation from [15], experimental points are the data at different altitudes (see [15, 16] for references).
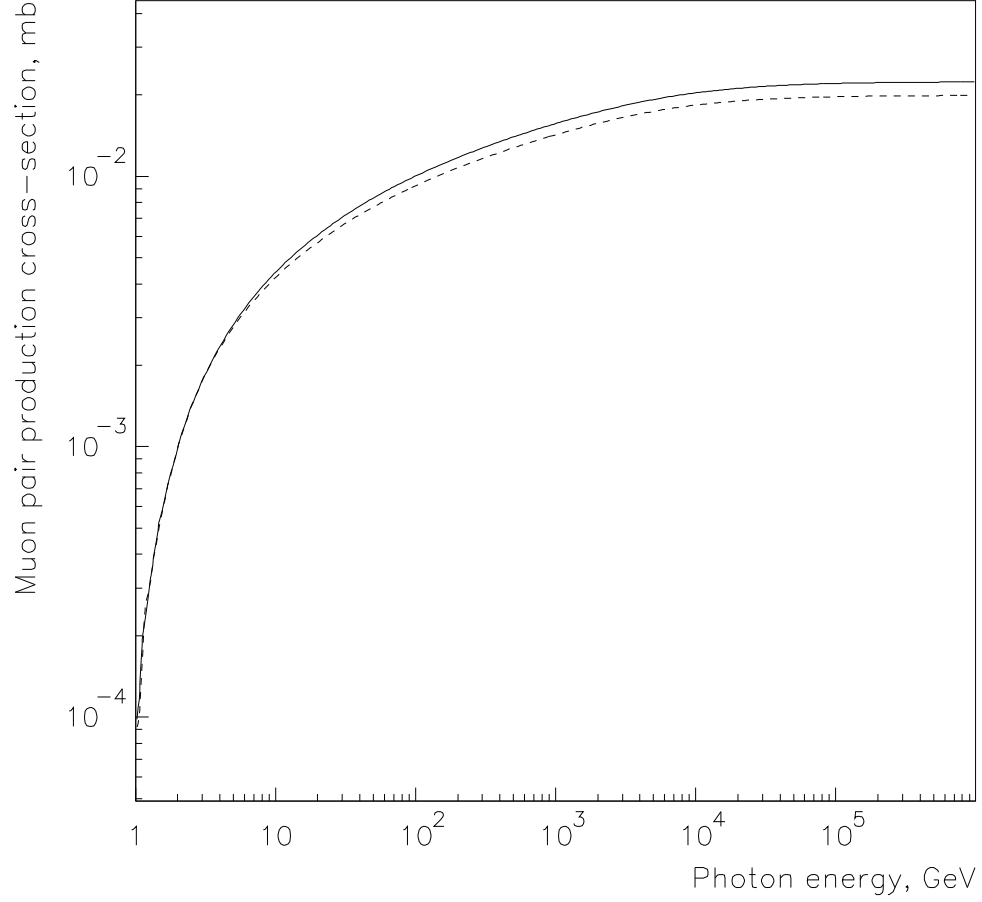
Figure 2: Muon pair production cross-section as a function of photon energy for two minimal values of fractional energy transfer: $x_{min} = E_{\mu min}/E_\gamma = 0.01$ (solid curve) and $x_{min} = 0.1$ (dashed curve).
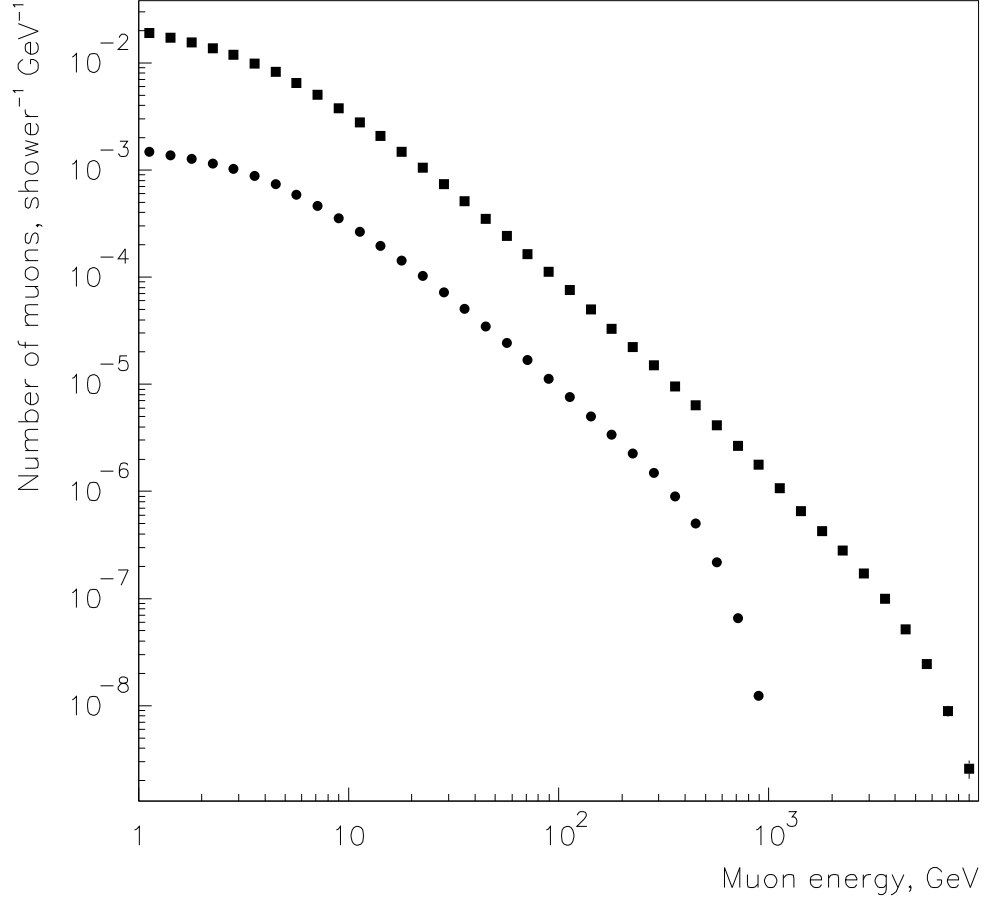
Figure 3: Differential muon spectra in electromagnetic showers at sea level at vertical for 1 TeV (filled circles) and 10 TeV (filled squares) primary photons.